Development of 400 Gb/s optical transceivers for SMF based datacenter optical interconnect

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***Abstract*—We reported the progress of developing 400-Gb/s optical transceivers with 1.3-μm electro-absorption modulators for optical interconnect applications in data centers. The key technologies include high-speed light sources, silicon photonics based WDM multiplexers/de-multiplexers, driving and receiving circuits, signal processing and monitoring schemes.**

Keywords—Optical transceivers, 400 Gb/s, optical interconnect, data centers

I. INTRODUCTION

The explosive applications of cloud computing, social networking, and high-definition video streaming, and internet of everything are driving the network bandwidth to increase exponentially, especially for interconnections in data centers. The 400-Gb/s optical interconnect will be soon deployed in and between data centers [1]. In this work, the progress on developing key technologies of 400-Gb/s optical transceivers for data center applications will be reported. This work is a joint efforts between academia, including research groups from three universities, and four industry partners.

Fig. 1 shows the framework of the research project funded by the Ministry of Science and Technology, Taiwan. It consists of 6 subprojects that are executed by the research groups from National Taiwan University, National Chiao-Tung University, and National Taiwan University of Science and Technology. The target of the project is to develop optical transceiver prototypes that can be commercialized by the industry partners. Fig. 2 shows the transceiver architecture that adopts 8 wavelength channels of 56-Gb/s to realize 400 Gb/s data rate for the optical interconnect. The technology development includes the multi-wavelength high-speed light sources, silicon photonics WDM multiplexers and de-multiplexers, high-speed circuit boards, transmitter modulation and driving circuits, receiver circuits, high-speed connectors, equalization techniques, and the performance monitoring. The technology development consists of devices, integrated circuits, circuit boards, and signal processing. Both directly modulated DFB lasers and electro-absorption modulated lasers (EMLs) are designed and fabricated to carry the high-speed data. The 56-Gb/s data rate is achieved by either NRZ or PAM-4 signals. In the following, some of the key achievements developed in this project will be reported.

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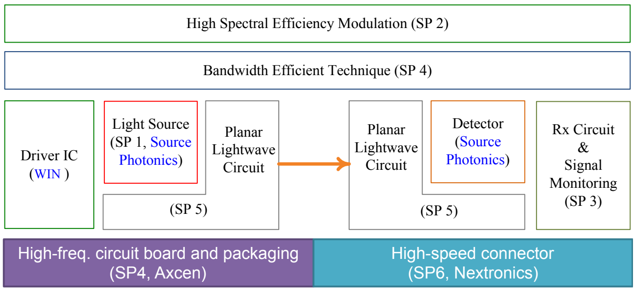


Fig. 1. Framework of the 400-Gb/s research project.

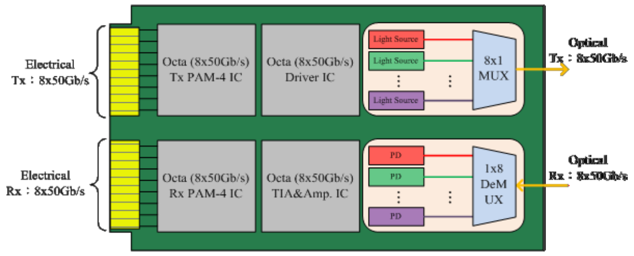


Fig. 2. Optical transceiver architecture

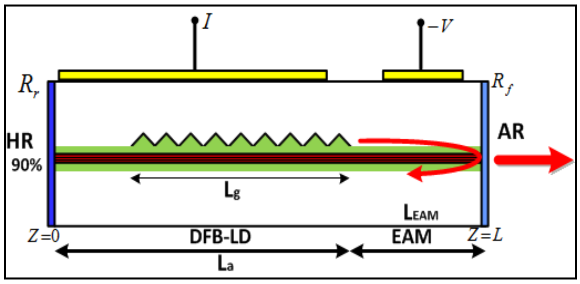
II. HIGH-SPEED LIGHT SOURCES

The goal is to develop DFB lasers and EMLs for transmitting 28-Gbaud/s PAM-4 signals. The DML has the merits of wide bandwidth and low chirp. However, if not designed carefully, the EML is vulnerable to the optical feedback effect and carrier trapping effects. This makes it difficult to screen the EMLs in production lines with only DC measurements since an EML can have very different dynamic characteristics from the static ones. The device screening by testing the output power and spectral characteristics cannot guarantee the yield of EMLs under high-speed modulation. However, screening with dynamic measurement is very time-consuming and costly. Therefore, the best strategy is to design EMLs with robust characteristics that are immune to residual facet reflection. We adopt the DFB laser with partial grating for integration with an EAM and optimize the grating length and gain coefficient so as to provide high device yield and good signal quality even with residual facet reflection.

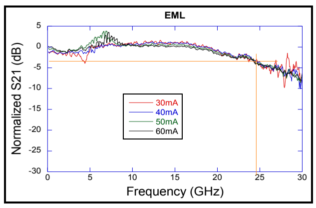
Fig. 3(a) shows the device structure of an EML with partial grating. The simulation and experiments verify that the use of partial gratings can improve the dynamic (RF) yield of the EMLs [2]. The EML can have 24-GHz bandwidth, as indicated by the S21 measurement shown in Fig. 3(b). Fig. 3(c) shows the measured eye pattern for transmitting 28-Gbaud/s PAM-4 signals over 2 km of SMF. The bit error rate is 7.7 x 10^{-4}.

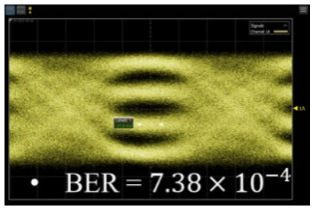
III. RECEIVER IC

The receiver circuits includes the trans-impedance amplifier (TIA), equalizer, AGC, and CDR. Fig. 4 shows a PAM-4 optical receiver front-end, which is composed of two low-noise shunt-feedback TIAs with an equalizer, an AGC amplifier, an offset canceling network, and a buffer. The AGC amplifier is composed of five dB-linear VGAs, a power detector, and an integrator. With AGC, the output level of PAM-4 signals can maintain a constant value. The designed receiver circuit was tape-out to TSMC. Fig. 5 shows the measured eye diagrams with an input 56Gbps PRBS of 2^7-1 PAM-4 signal. Eye openings can be obtained with the receiver front-end.



(a)





(b) (c)

Fig. 3. Optical transceiver architecture

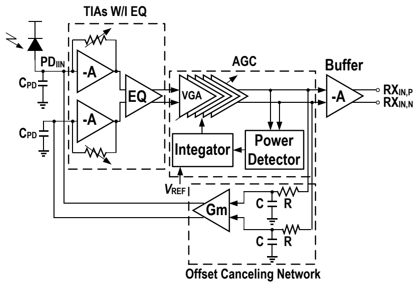


Fig. 4. 56Gbps PAM-4 optical receiver front-end

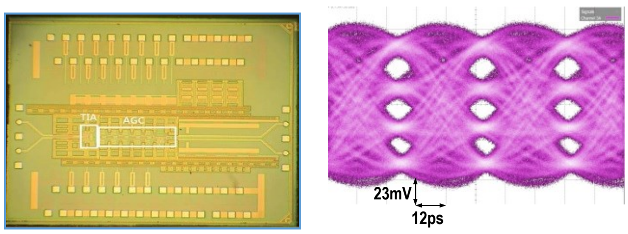


Fig. 5. The receiver front-end chip and measured eye diagram.

IV. MUX AND DEMUX DESIGN

The goal is to design 4-channel CWDM and 8-channel LAN-WDM multiplexers (Mux) and de-multiplexers (DeMux). Eight-channel wavelength-division-multiplexers are needed to realize the 8x50Gb/s optical transceivers for emerging 400Gb/s Ethernet solutions [1]. The wavelength plan of this solution is an expansion of the wavelength allocation for 4-wavelength 100G-Ethernet, which is also called LAN-WDM. The eight lanes (L0 to L7) are divided into two groups with 800-GHz channel spacing inside each group and 1600 GHz spacing between L3 and L4. The DeMux of the 8 lanes can be realized with arrayed waveguide grating (AWG) [3] or thin-film coated bulk optics. The AWG DeMux is very sensitive to waveguide phase errors, so it is usually fabricated on low-index-contrast silica waveguides and has relatively large size.

To meet the demand of ever shrinking transceiver size, we report here a design of very compact 8-channel DeMux by using the silicon-on-insulator (SOI) platform and verify its flat-top passband and high channel isolation by simulation. The device is formed by grating-assisted contra-directional couplers (GACDC) with a novel design of the coupling structure.

The device includes a Mach-Zehnder Interferometer (MZI) based band filter and four drop filters made of GACDC segments. The band filter separates the 8 channels into 2 groups of 4 to reduce the number of cascaded drop filters and reduce the insertion loss. There are 2 drop filters in each branch and each drops 2 channels. The schematic of each drop filter is depicted in Fig. 6.

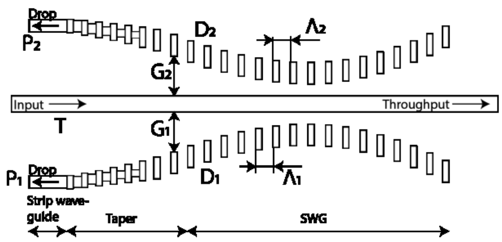


Fig. 6. Schematic of grating assisted contra-directional coupler.

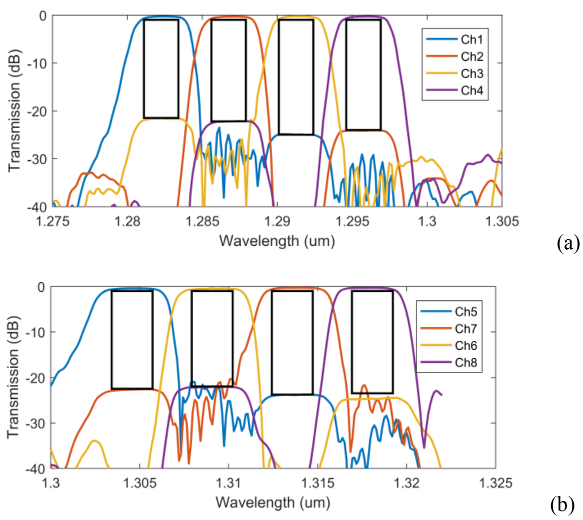


Fig. 7. Spectral response of (a) channels 1to 4 and (b) channels 5 to 8.

The simulated spectral responses of the demultiplexer are shown in Fig.7(a) for Channel 1 to 4 and Fig.7(b) for Channel 5 to 8. Flat-top channel characteristics can be obtained for all the channels with an insertion loss of less than 0.8 dB and a bandwidth of more than 2.3 nm. These results do not include the insertion loss of the bandpass filter. Suppression of adjacent channels is better than 22 dB for all channels; and most of the crosstalk comes from the partial coupling from the other channel in the same drop filter section.

V. Optical Equaltion

The realization of high-speed light sources that have enough bandwidth for 28-Gbaud/s PAM-4 signals is very challenging. PAM-4 signals require shorter transit time than conventional NRZ signals. For light sources with insufficient bandwidth, the optical filtering scheme can be used to provide optical equalization, which can relax the need of electric equalization.

Spectrum reshaping using an optical filter has been demonstrated for NRZ signals so as to reduce the dispersion effect caused by the chirp effect of a DML [4]. We have previously demonstrated that the spectral reshaping can have three effects: enhancement of extinction ratio (ER), chirp management, and equalization by conversion of frequency modulation to amplitude modulation (FM2AM) [4]. The FM2AM effect can enhance the high-frequency (HF) response due to the stronger HF content for FM than AM. We adopt this concept to enhance the signal response of PAM-4 such that the inter-symbol interference (ISI) can be reduced. The challenge for using the FM2AM function to PAM-4 signals is the nonlinear effect caused by the conversion that will distort the eye openings of the four levels. Highly linear circuits are typically used for processing PAM-4 signals. That is, PAM-4 signals have 4 equally-spaced levels that can be influenced seriously by aligning their spectrum at the slope of the optical filter.

The system architecture for experiments is shown schematically as Fig. 8. A diffraction grating is used as the optical filter to reshape the optical PAM-4 signals generated from a DML, which has 14 GHz of 3-dB modulation bandwidth. There exists an optimal wavelength position between the optical filter and the DML to enhance the PAM-4 signal. Fig. 9 (a) shows the poor eye diagram without optical equalization due to insufficient bandwidth of the DML. After passing through the optical filter, the PAM-4 signal can have much improved eye patterns, as shown in Fig. 9(b).

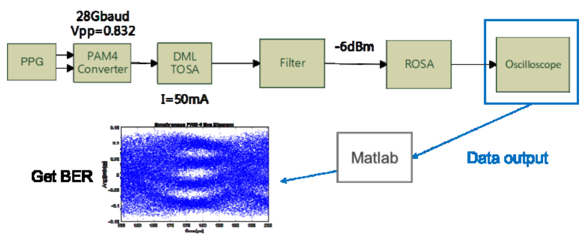
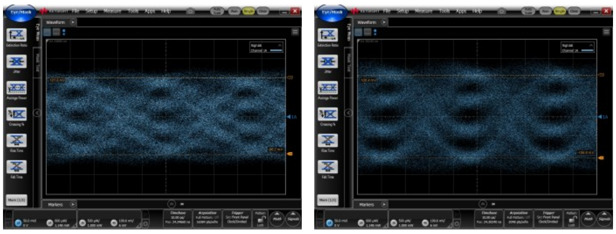


Fig. 8. Experimental setup for optical equalization..



(a) (b)

Fig. 9. Eye daigram (a) before and (b) after optical filtering.

VI. ELECTRIC EQUALIZER

We have also designed a novel convolutional neural network based nonlinear classifier that outperforms traditional Volterra nonlinear equalizers. A BER of 3.50×10^{-6} is obtained for a 112-Gbps PAM4 EML-based optical link over 40-km SMF transmission.

The schematic diagram of our proposed system is shown in Fig.10. Four 28 Gbauds NRZ signals with pseudo-random bit sequence (PRBS) of length $2^{15}-1$ are generated by an Anritsu MP1800A pulse pattern generator (PPG). These four signals are divided into two pairs; each pair forming a 4-PAM signal, and then the two 4-PAM signals are combined to double the transmission speed to 56 Gbauds. The electrical signal is sent to an electro-absorption modulated laser (EML, NeoPhotonics OL3175M-2L0, with wavelength of 1293 nm). A variable optical attenuator (VOA) is used to control the output power of a semiconductor optical amplifier (SOA) and the fiber launch power is set at 12 dBm. After 40-km SMF transmission, another VOA is used to adjust the received power. The optical signal is detected by a 30-GHz photo-receiver (Picometrix PT-28E), and the electrical signal is recorded by a digital storage oscilloscope (Tektronix® MSO 73304DX) with a 100-GS/s sampling rate and 3-dB bandwidth of 33 GHz. The CNN (convolution neural network)- and DNN (deep neural network)-based NLC (non-linear classifier) is implemented to restore the original data pattern. We compiled our model in Python® with a GPU-supported TensorFlow® library, which is developed by the Google Brain team.

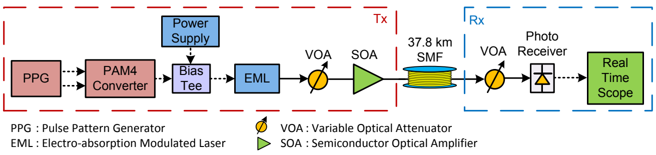


Fig. 10. Schematic diagram of 112-Gbps 4-PAM optical link.

The training set contains 20,000 bits and 800,000 bits in the testing set. The performance of our proposed system is measured using the bit-to-bit error count. We divided the total data into four different test sets and the BER are measured at -8 dBm for both CNN and DNN. The CNN has almost 10 times better average BER than DNN, as shown in Table 1.

TABLE I. BER OF DNN AND CNN

		Test 1	**Test 2**	**Test 3**	**Total**
b2b	***CNN***	1.53E-05	1.53E-05	3.57E-05	2.21E-05
	DNN	1.73E-05	2.04E-05	5.82E-05	3.20E-05
40 km	***CNN***	1.73E-05	2.44E-05	1.08E-04	4.98E-05
	DNN	7.02E-05	9.97E-05	4.65E-04	2.12E-04

VII. CONCLUSIONS

We have reported some technology development for realizing 400-Gb/s optical transceivers for data center optical interconnects. EMLs for 28-Gbaud/s PAM-4 modulation and the receiver circuits are successfully fabricated. The designed 8-channel WDM Mux/DeMux has been tape-out for fabrication by a semiconductor foundry. The optical equalization technique is demonstrated to enhance the signal quality of optical PAM-4 signals generated by a DML with insufficient bandwidth. A novel convolutional neural network based nonlinear classifier is demonstrated to outperform traditional Volterra nonlinear equalizers. In the presentation, we will also cover some results with the PAM-4 signal monitoring and high-speed connector design.

The system loss budget is 20 dB at 12 dBm launch power. Considering 13 dB loss after 40-km SMF fiber and total 4 dB loss for Mux and DeMux, it still has 3 dB margin to support a 4-channel wavelength-division multiplexing (WDM) system for the 400-Gbps (4×100) requirement in extended-reach.

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